Reproducibility Limits of Night Vision Goggle Visual Acuity Measurements

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ABSTRACT

The main purpose of the study was to determine reproducibility limits of night vision goggle (NVG) visual acuity measurement under relatively high and low illumination levels. Psychometric acuity functions of three observers were repeatedly measured using Landolt C's as stimuli. The reproducibility limits of the Snellen acuity value (20/xx) relating to 50, 75 and 95% correct (adjusted for chance) were then determined. Reproducibility limit is defined as approximately 95% of all pairs of replications (20/xx) from the same illuminance and same observer, generated on different days, should differ in absolute value by less than the reproducibility limit. It was determined that for the lower illumination (8.61E-4 lux) at 50% corrected for chance probability level, the reproducibility limit was 5.1 Snellen acuity (20/xx) and for the higher illumination (1.38E-2 lux), 2.5 Snellen acuity. These limits were 17% and 13% of mean acuity, respectively.

INTRODUCTION and BACKGROUND

There are numerous methods used to determine night vision goggle (NVG) visual acuity (Pinkus & Task, 1998); limiting resolution (Stefanik, 1994; Task, 1979), Snellen Acuity (Bailey & Lovie, 1976; Wiley, 1989; Miller, Provines, Block, Miller & Tredici, 1984), square-wave targets (Task & Genco, 1986), Landolt C's (Pinkus & Task, 1997), adaptive psychophysical (Simpson, 1989) and directly measuring the psychometric function (Pinkus & Task, 1998; Brown, Galanter, Hess, & Mandler, 1962). Each method produces a number that is composed of the actual acuity value plus error. There can be many sources of error but the largest are the method itself and the inherent variability of the observer while working under threshold conditions. Observer variability is reduced to a minimum through extensive training, testing the same time everyday and shortened sessions in order to reduce eye fatigue. Additionally, even though observers are given specific instructions, response criteria also vary among or within observers; even over the course of a single experimental session. To eliminate the *criteria problem*, Pinkus & Task (1998) used Landolt C's in a four-alternative forced-choice (4AFC) paradigm to measure the entire psychometric function. This paradigm allowed for any desired response criterion level (e.g., 50% or 75% corrected for chance, probability of detection) to be selected for the prediction of NVG visual acuity performance.

The goal in this study was to select a stable method and then determine its reproducibility (ASTM Practice E 691). Reproducibility represents observation-to-observation variability under a given set of viewing conditions. Directly measuring the psychometric function should keep variability due to the test method to a minimum. Determining reproducibility will allow the use of this test method to determine NVG visual acuity with a known error tolerance. The interpretation of visual acuity data is investigated in the discussion section.

METHOD

Participants

The trained observers were one female and two males highly experienced with the operation of NVGs. They ranged in age from 37 to 47 years, each having normal (20/20) or corrected-to-normal binocular visual acuity.

Apparatus and Stimuli

NVGs - Participants viewed the target stimuli using a pair of ITT model F4949D (SN 3872) NVGs. The goggles had a gain of approximately 5600 as measured using the Hoffman ANV-120 NVG Test Set. Before the start of each test session, the optical alignment of the NVGs was

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verified using the Hoffman ANV-126 Night Vision Tester.

Each test session was conducted in a light-tight laboratory. The observer was seated at an optical table with the NVGs secured in a stationary mount directly in front of them. The observer was able to adjust their seat to the proper height for viewing through the NVGs. An external regulated power supply was used to energize the goggles.

At the beginning of each test session the observer would set up and pre-focus the NVGs using the following procedure. After dark-adapting for 15 minutes, the NVGs were powered on and the observer adjusted the inter-pupillary distance until a fused circular image was visible. The observer (using their dominant eye) focused one channel at a time. The observer first focused on the green scintillation by looking at the ceiling and adjusting the eyepiece until the focus of the scintillation was as sharp as possible. Next, the observer focused the corresponding objective lens by viewing the 3 x 3A, NVG high-contrast square-wave resolution chart (Task and Genco, 1986) located at a 30 ft distance (optical infinity). The objective lenses were pre-focused using the highest illumination level (1.38 x 10-2 lux). A higher illumination level allows the observer finer, low noise focusing. The observer chose the finest grating clearly resolvable and adjusted the objective lens to the sharpest focus possible. If necessary, the observer fine tuned the eyepiece while viewing the chart. These steps were repeated for the second channel.

Illumination source and Illumination levels - Table 1 shows the illumination levels and corresponding NVG eyepiece luminance outputs. The lowest illumination level

Table 1. The two illumination levels (average) and corresponding NVG output luminances (average) for this study.

ILLUMINATION ON LANDOLT C	NVG OUTPUT LUMINANCE
8.61×10^{-4} lux (8.00×10^{-5} fc)	0.356 nit (0.104 fL)
1.38×10^{-2} lux (1.28×10^{-3} fc)	4.324 nit (1.262 fL)

is approximately equivalent to 1/300th full moon (RCA Electro-Optics Handbook, 1974, p. 65) while the highest illumination level is 16 times brighter. The low illumination level corresponds to a practical lower limit under which goggles are used in the field. The higher level corresponds to an approximate ¼ moon level. Target stimuli were illuminated by one or two moon illumination

lamps outfitted with adjustable 2856K color temperature incandescent bulbs (MIL-L-8576A, 1986). Metal apertures were used to achieve the two illumination levels. Using apertures to vary illumination intensity did not affect the 2856K color temperature. The target illumination levels were measured and adjusted prior to each test session. The goggle output luminances were measured using a NVG photometer (Pinkus, 1991).

Landolt C test stimuli and automated data recording device - Test stimuli were Landolt C's. The C's were printed using a high resolution, photo-grade laser printer. They were high contrast (67% photopic, Michelson; Farrell & Booth, 1984) Landolt C's (National Academy of Sciences, 1980) printed using a high resolution, photo-grade laser printer. The print out of each target was mounted on 18 cm x 18 cm (7" x 7") squares of foam board. Each target varied in gap size and represented, when converted, a specific Snellen visual acuity value (20/xx). The back of each target was labeled with four different bar code patterns. Each bar code contained identification information such as target number, type, contrast, gap orientation and corresponding visual acuity (20/xx). On each experimental trial, a Landolt C was placed in the center of a larger foam board surround 56 cm x 56 cm (22" H x 22" L). The surround had the same reflectance as the background of the Landolt C's. This surround was secured to the front of a black light-tight wooden box. The box measured 66 cm H x 56 cm W x 36 cm L (26 H x 22" W x 14" L) and sat on top of a stand. This box housed a bar code scanner/reader used to automate the recording of Landolt C target information. The light-tight box prevented the incompatible red laser beam from the bar code scanner from affecting the NVGs. The bar code reader connected directly to a computer at the experimenter's station. The entire set up was positioned at 914 cm (30 feet) or optical infinity from the observer. A four button response box located next to the observer was also connected to the computer. The observer used the buttons to indicate the orientation of the Landolt C gap (up, down, left or right). The computer recorded the button press response and Landolt C bar code information as well as other pertinent information.

Procedure
Three trained observers participated in this study. Each observer completed 2 sessions per day on each of 3 days. Each session (140 randomized trials) used an illumination level of either 8.61E-04 or 1.38E-2 lux (target background reflectance's were 5.64E-5 and 9.03E-4 lux, respectively). At the beginning of each test session, the observer dark-adapted for approximately 15 minutes. The observer then turned on and focused the NVGs. For each trial, the experimenter, using pre-determined randomized stimuli

ordering, placed a Landolt C onto a small ledge on the surround and kept it blocked from the observer's view. This ledge centered the 'C' and was not noticeably visible when viewed through the NVGs. The experimenter pressed a switch to scan the bar code on the back of the target. The experimenter would then move away from the Landolt C and the observer had about four seconds to view the stimulus. At the end of the four-second interval the computer would beep an alarm and the experimenter would immediately block the stimulus from the observer's view. The observer would press the appropriate button on the response box to indicate what direction the gap was oriented: up, down, left or right. The observer was not provided with any feedback on their performance. This sequence of events was repeated until 140 trials were completed (7 Landolt C target sizes x 4 orientations x 5 repetitions of each orientation). The 7 target sizes are Snellen acuity values (i.e., 20/xx).

RESULTS

Probit analysis was used to determine the observer's acuity, for each replication, that corresponded with 50%, 75%, and 95% correct adjusted for chance. These acuity values were then used to determine the reproducibility limit as previously defined.

Table 2 contains the percent of correctly identified orientations out of the 20 trials (4 orientations x 5 repetitions) for each combination of illuminance, observer, acuity, and replication. Chance alone would result in 25% correctly identified trials. It is assumed that percents that are less than 25% would approach 25% with a sufficient number of trials. The percents were transformed to adjust for chance. The procedure for this transformation was as follows:

Let: P = percent correct trials
P_A = percent correct trials adjusted for chance
(1) if P < 25 then P = 25
(2) $P_A = (P-25) * 100/75$

For probit analysis, adjusted percents are converted to normal equivalent deviates (NED). An NED is the value of a standard normal variable whose cumulative probability (expressed as a percent) would equal the percent correct adjusted for chance. The NED values are then used as the dependent variable in a linear regression with acuity as the independent variable, where a linear relationship is assumed (Finney, 1980). The estimated $NED=b_0+b_1*acuity$ is then transformed back to percents. The resulting estimates of P_A form a curvilinear function.

If there is a range of acuity values where P_A is near 0 or P_A is near 100, the relationship between NED and acuity will not be linear. The rationale for selecting percents used for modeling was to start with the largest acuity value where the observer was guessing (correct ≤ 7 out of 20 was used) if applicable, and end with the smallest acuity value where $P_A=100$, if applicable. Since an NED cannot be computed for 0% or 100%, 0% was set to 1% and 100% was set to 99%. Correct ≤ 7 was used as a 'guessing' cutoff since the probability of 8 ≤ Correct is 0.10 by chance alone. Table 3 contains the percent of correctly identified orientations out of the 20 trials (4 orientations x 5 repetitions), adjusted for chance, for each combination of illuminance, observer, acuity, and replication. Results of NED regressed on acuity are shown in Figures 1a and 1b.

Table 2. Percent correct trials (N=20) for each illuminance, observer, acuity, and replication.

Illuminance (lux)	Observer #1				Observer #2				Observer #3			
	Snellen Acuity (20/xx)	% Correct			Snellen Acuity (20/xx)	% Correct			Snellen Acuity (20/xx)	% Correct		
		Replication				Replication				Replication		
		1	2	3		1	2	3		1	2	3
8.61E-4	24.8	55	35	45	24.8	35	65	45	26.7	35	50	47
	26.7	20	50	45	26.7	45	45	55	28.6	15	45	48
	28.6	65	37	75	28.6	50	60	70	30.6	50	70	55
	30.6	65	45	85	30.6	90	70	80	32.5	60	85	90
	32.5	90	58	90	32.5	80	80	85	34.4	75	80	89
	34.4	100	85	95	34.4	70	95	75	36.3	90	75	95
	36.3	100	75	100	36.3	90	85	90	38.2	100	95	95
1.38E-2	13.4	30	45	20	13.4	25	20	20	13.4	35	15	30
	15.3	20	30	45	15.3	30	40	50	15.3	35	25	30
	17.2	35	55	45	17.2	50	50	60	17.2	35	55	45
	19.1	70	75	45	19.1	80	45	85	19.1	75	80	70
	21.0	75	85	85	21.0	95	80	65	21.0	90	100	100
	22.9	65	85	100	22.9	100	95	80	22.9	90	100	100
	24.8	85	85	95	24.8	100	80	80	24.8	100	100	100

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Table 3. Percent correct trials (N=20), adjusted for chance, for each illuminance, observer, acuity, and replication. Percents in italic were not used for modeling.

| Illuminance (lux)	Observer #1 Snellen Acuity (20/xx)	% Correct Replication 1	2	3	Observer #2 Snellen Acuity (20/xx)	% Correct Replication 1	2	3	Observer #3 Snellen Acuity (20/xx)	% Correct Replication 1	2	3
	24.8	40	13	27	24.8	13	53	27	26.7	*13*	33	30
	26.7	0	33	27	26.7	27	27	40	28.6	0	27	30
	28.6	53	16	67	28.6	33	47	60	30.6	33	60	40
8.61E-4	30.6	53	27	80	30.6	87	60	73	32.5	47	80	87
	32.5	87	44	87	32.5	73	73	80	34.4	67	73	86
	34.4	100	80	93	34.4	60	93	67	36.3	87	67	93
	36.3	*100*	67	100	36.3	87	80	87	38.2	100	93	93
	13.4	7	27	0	13.4	*0*	0	0	13.4	*13*	0	7
	15.3	*0*	7	27	15.3	7	20	33	15.3	*13*	0	7
	17.2	13	40	27	17.2	33	33	47	17.2	13	40	27
1.38E-2	19.1	60	67	27	19.1	73	27	80	19.1	67	73	60
	21.0	67	80	80	21.0	93	73	53	21.0	87	100	100
	22.9	53	80	100	22.9	100	93	73	22.9	87	*100*	*100*
	24.8	80	80	*93*	24.8	*100*	73	73	24.8	100	*100*	*100*
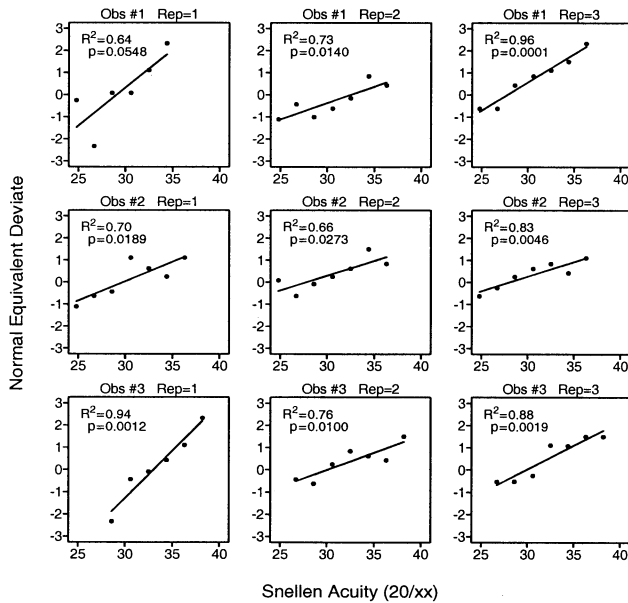
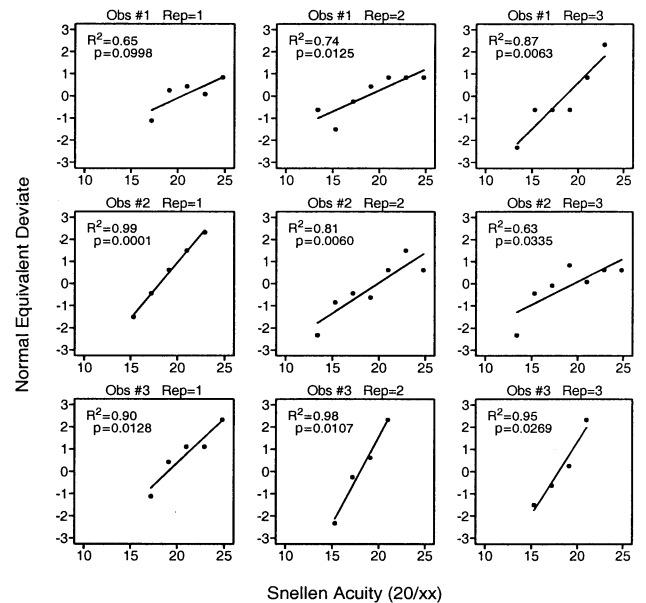Figure 1a. For illuminance = 8.61E-4 lux, results of NED regressed on acuity for each observer and replication.

Figure 1b. For illuminance = 1.38E-2 lux, results of NED regressed on acuity for each observer and replication.

The estimated NED = b_0+b_1*acuity, as shown in Figures 1a and 1b, was transformed back to percents. For each illuminance, observer, and replication, the acuity that related to predicted 50, 75, and 95 percent correct adjusted for chance was determined. Plots of the predicted percents are shown in Figures 2a and 2b. Results are shown in Table 4. The reproducibility limits of the acuity value (20/xx) relating to 50, 75, and 95 percent correct

adjusted for chance were determined. Reproducibility limit is defined as: approximately 95% of all pairs of replications (20/xx) from the same illuminance and same observer, generated on different days, should differ in absolute value by less than the reproducibility limit. Table 5 contains the reproducibility limits.
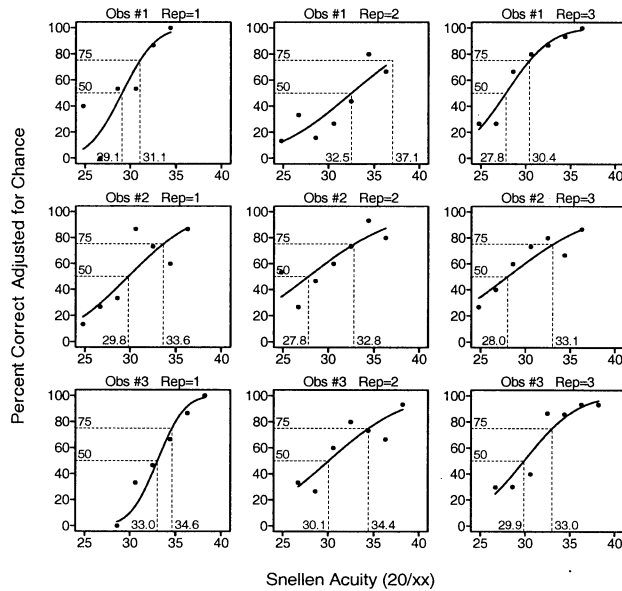

Figure 2a. For illuminance = 8.61E-4 lux, predicted percent correct adjusted for chance, for each observer and replication. Acuity values are given that relate to 50 and 75 percent correct adjusted for chance.
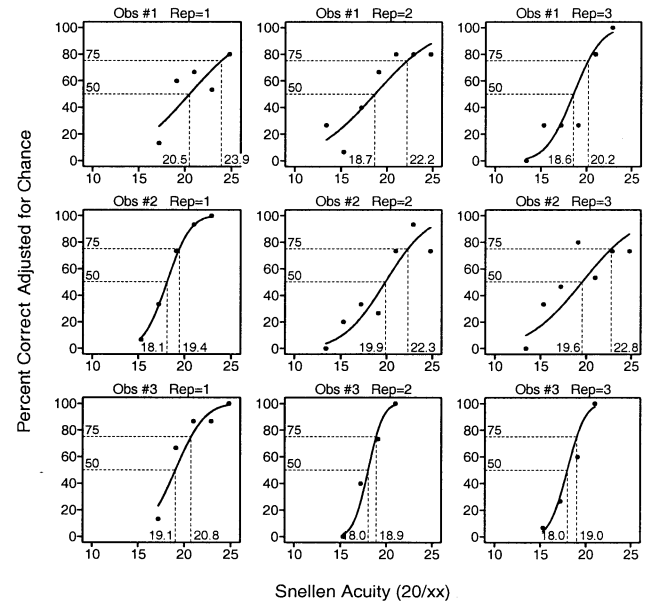

Figure 2b. For illuminance = 1.38E-2 lux, predicted percent correct adjusted for chance, for each observer and replication. Acuity values are given that relate to 50 and 75 percent correct adjusted for chance.

Table 4. Snellen acuity values (20/xx) relating to predicted 50, 75, and 95 percent correct adjusted for chance, for each illuminance, observer, and replication.

Illuminance (lux)	Observer	50% Replication			75% Replication			95% Replication		
		1	2	3	1	2	3	1	2	3
8.61E-4	#1	29.1	32.5	27.8	31.1	37.1	30.4	33.9	43.6	34.2
	#2	29.8	27.8	28.0	33.6	32.8	33.1	39.1	40.0	40.4
	#3	33.0	30.1	29.9	34.6	34.4	33.0	36.9	40.7	37.6
1.38E-2	#1	20.5	18.7	18.6	23.9	22.2	20.2	28.9	27.3	22.5
	#2	18.1	19.9	19.6	19.4	22.3	22.8	21.4	25.9	27.4
	#3	19.1	18.0	18.0	20.8	18.9	19.0	23.2	20.1	20.5

Table 5. Snellen acuity reproducibility limits (20/xx)
for each illuminance and percent correct adjusted for chance.

Illuminance (lux)	% Correct (Adjusted)	Mean Acuity (20/xx)	RL (20/xx)	RL % of Mean
8.61E-04	50	29.8	5.1	17
	75	33.3	6.1	18
	95	38.5	9.4	24
1.38E-02	50	18.9	2.5	13
	75	21.1	4.5	21
	95	24.1	7.8	32

The same procedure for determining the predicted percent correct adjusted for chance that was performed for each illuminance, observer, and replication was also performed for each illuminance and observer, summed across replications. Table 6 contains the percent of trials correctly identified for each combination of illuminance, observer, and acuity. Figure 3 contains NED regressed on acuity. Figure 4 contains plots of the predicted percents. Table 7 contains the acuity values corresponding to predicted 50, 75, and 95 percent correct adjusted for chance.

Table 6. Percent correct trials (P) and percent correct trials adjusted for chance (P_A),
for each illuminance, observer, and acuity. Trials have been summed
across replications (N = 60). P_A in italics were not used for modeling.

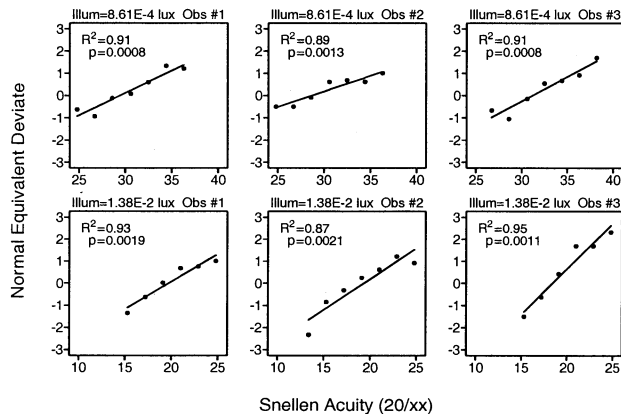| Illuminance (lux)	Observer #1			Observer #2			Observer #3		
	Snellen Acuity (20/xx)	Percent Correct		Snellen Acuity (20/xx)	Percent Correct		Snellen Acuity (20/xx)	Percent Correct	
		P	P_A		P	P_A		P	P_A
8.61E-4	24.8	45	27	24.8	48	31	26.7	44	25
8.61E-4	26.7	38	18	26.7	48	31	28.6	36	15
8.61E-4	28.6	59	46	28.6	60	47	30.6	58	44
8.61E-4	30.6	65	53	30.6	80	73	32.5	78	71
8.61E-4	32.5	80	73	32.5	82	76	34.4	81	75
8.61E-4	34.4	93	91	34.4	80	73	36.3	87	82
8.61E-4	36.3	92	89	36.3	88	84	38.2	97	96
1.38E-2	13.4	32	9	13.4	22	0	13.4	27	2
1.38E-2	15.3	32	9	15.3	40	20	15.3	30	7
1.38E-2	17.2	45	27	17.2	53	38	17.2	45	27
1.38E-2	19.1	63	51	19.1	70	60	19.1	75	67
1.38E-2	21.0	82	76	21.0	80	73	21.0	97	96
1.38E-2	22.9	83	78	22.9	92	89	22.9	97	96
1.38E-2	24.8	88	84	24.8	87	82	24.8	100	100

Figure 3. Results of NED regressed on acuity for each illuminance and observer.
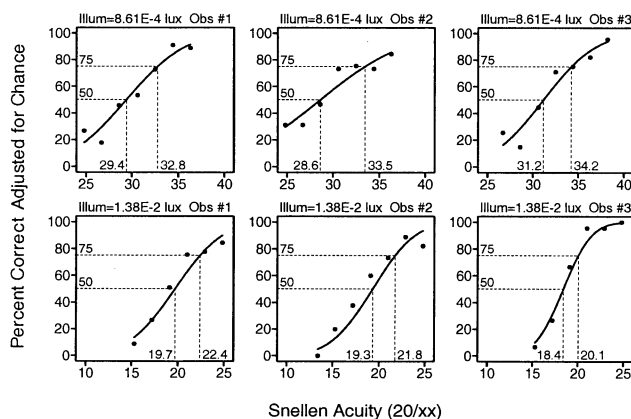

Figure 4. Predicted percent correct adjusted for chance, for each illuminance and observer. Acuity values are given that correspond to 50 and 75 percent correct adjusted for chance.

Table 7. Snellen acuity values (20/xx) corresponding to predicted 50, 75, and 95 percent correct adjusted for chance, for each illuminance and observer.

Illuminance (lux)	Observer	50%	75%	95%
8.61E-4	#1	29.4	32.8	37.6
	#2	28.6	33.5	40.4
	#3	31.2	34.2	38.6
1.38E-2	#1	19.7	22.4	26.3
	#2	19.3	21.8	25.2
	#3	18.4	20.1	22.4

DISCUSSION

Table 5 summarizes the Snellen acuity reproducibility limits at the two illumination levels for three levels of percent correct (adjusted for chance). The 50%, 75% and 95% percent levels represent threshold, a just-noticeable-difference (JND) above threshold and a conservative, high-confidence gap detection, respectively. The reproducibility limits, when taken as a percent of the mean, show similar variability at both the lower and higher illuminance conditions.

One way to apply the reproducibility limit is to use it to assign a range for a given NVG visual acuity measurement. Many times, the interactions between NVGs and other cockpit subsystems such as a gold-coated canopy or an incompatible light source, are evaluated by making only a few NVG visual acuity measurements (baseline versus a test condition) using just a couple of observers. The problem with this approach is that the variability that is inherent in both the test method and the observer can easily mask the true NVG acuity effects. The reproducibility limits at the 50% correct were approximately 15% of the mean acuity values (for this specific lab methodology only). When interpreting field data acuity results, 95% of all absolute differences in observations should differ by less than 15% of the mean acuity if variability is due solely to experimental error. If the data varies more than 15% than there are additional sources of variability such as the infrared-attenuating effects of canopy coating on NVG visual acuity. For example, if, under low light levels, an observer reports an NVG visual acuity baseline of 20/30 and then 20/35 while looking through a coated canopy, one might (erroneously) conclude that the canopy caused a large loss of acuity which translates into a loss of target acquisition slant range. The difference between 20/30 and 20/35 is 5 which when divided by their average of 32.5 equals 0.15 or 15%. A difference of five then is approximately at the 95 percentile of acuity differences under the same viewing conditions. Therefore, these example data are at the outer limit of variability due solely to experimental error implying that small differences found in field measurements are questionable. The reproducibility value of 15% of the mean acuity value is a good estimate for field tests. If the tests are conducted under more conservative criteria (75% correct), then about 20% applies.

CONCLUSIONS

One problem we have observed in this and other studies is that of interpretability. Observers reliably report seeing Landolt C gaps at relatively high visual acuity's of 20/20 and better, even under degraded viewing conditions such as low-light levels or noisy (scintillation) conditions. But

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does the observer really see the gap? When working at noisy threshold levels the gap can appear to move around to the four different locations or alternately open and close. Sometimes no gap is seen at all, maybe just a lighter area or a circle having a flat side. When the observer *correctly* responds to this flat side, we interpret the correct response as a seen gap having a specific size indicating a specific visual acuity which may explain higher than expected visual acuity's. This problem underlies all acuity measurements thus affecting interpretability and conclusions of studies' findings. To try to reduce this effect the stimulus duration was held to four seconds. The current method of stimulus presentation makes shorter, precise duration's difficult. A tachistoscope-type apparatus suited for NVG optics will have to be designed for the next study that will examine the effects of short-duration stimulus presentations on NVG acuity.

ACKNOWLEDGEMENTS

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BIOGRAPHIES

Alan Pinkus has been a US Air Force research psychologist since 1982. As a human factors engineer, he has worked on major systems including the Royal Saudi Air Force KE-3 tanker, Gunship 2, LANTIRN, Air Force One and Joint-Stars. As a researcher, he has worked in the areas of image display metrics, night vision goggles, apparent motion, aircraft lighting, transparency analysis, vision from space, workload assessment and has lectured for NATO AGARD in Europe. Alan has a BS Degree (Wright State University, 1974), an MA (University of Dayton, 1980) and a PhD (Miami University, 1992), all in Experimental Psychology. He holds nine patents in the area of night vision goggle ancillary devices and has over 25 publications. He is a member of SAFE, Association of Aviation Psychologists, the Human Factors and Ergonomics Society (Southern Ohio Chapter) and is the vice-chairman of the American Society for Testing and Materials Subcommittee (ASTM) F7.08 on Transparent Enclosures and Materials.

H. Lee Task has been employed as a research scientist for the US Air Force since 1971. He has served as chief scientist for the Armstrong Aerospace Medical Research Laboratory (prior to its reorganization and disestablishment in 1991) and is presently a senior scientist at the Visual Display Systems Branch of the Human Engineering Division, in the Armstrong Laboratory's Crew Systems Directorate, at Wright-Patterson AFB, Ohio. He is currently involved in research and development in the areas of helmet-mounted displays, vision through night vision goggles, optical characteristics of aircraft canopies, vision, and display systems. He has a BS Degree in Physics (Ohio University), MS degrees in Solid State Physics (Purdue, 1971), Optical Sciences (University of Arizona, 1978), and Management of Technology (MIT, 1985) and a PhD in Optical Sciences from the University of Arizona Optical Sciences Center (1978). During his career he has earned 36 patents and has published more than 80 journal articles, proceedings papers, technical reports, and other technical publications. He is a member of the Human Factors and Ergonomics Society (HFES), the American Society for Testing and Materials (where he is chairman of Subcommittee F7.08 on Aerospace Transparencies and is a Fellow of the Society), the Association of Aviation Psychologists, SAFE association, the Society for Information Display (SID), and SPIE (the optical engineering society). He has served as reviewer for papers in SID, and HFES. Lee is currently the Editor of the *SAFE Journal*.

Sharon Dixon is a contractor with Sytronics, Inc., with eleven years experience as a human factors psychologist. As a research assistant, she has worked in the areas of subjective mental workload, cognition, situation awareness, NVG-weighted canopy transmissivity, night vision goggles and panoramic night vision goggles. She has nine publications. Sharon has a BS degree in Human Factors Psychology from Wright State University (1987).

Charles Goodyear is a statistical consultant who, for the past 16 years, has either contracted with or consulted for researchers at the Air Force Research Laboratory at Wright-Patterson AFB, Ohio. He has a BS degree in Mathematics (1977) and a MS degree in Statistics (1982) both from Miami University in Oxford, Ohio.